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A Study of Tau Decays of the W Boson at CDF*

The CDF Collaboration

presented by

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Abstract

A report is given of a search for tau decays of the W boson in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the Collider Detector at Fermilab (CDF). A description of a hardware trigger specifically designed to enhance the number of events with tau decays is presented along with the results of a preliminary analysis of data taken during the 1988-89 run of CDF.

Introduction

Due to the ease of their detection, electrons and muons have been the principal means by which physicists search for and study massive, weakly decaying particles such as the top quark, W and Z bosons, etc. According to the Standard Model of weak interactions, however, there must be a "universality" in the strength of the couplings of the weak charged current to electrons, muons, and tau leptons. Hence, the tau should not be ignored in the study of $p\bar{p}$ interactions for several reasons. First, direct confirmation of the universality of the weak charged current coupling to the tau at high Q^2 has been made by only a single experiment[2]. Second, the heavy mass of the tau (and hence its ability to decay to hadrons) allows its unique use as a probe of the handedness of the coupling to the standard quarks and leptons to any new weak

*A list of the collaborating institutions appears in reference 1.

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bosons which may be discovered at the Tevatron or the SSC[3]. Third, taus may form one of the dominant, and more tractable, decay modes for charged Higgs bosons, should they exist[4]. Generation-changing horizontal gauge bosons may also couple preferentially to the tau since it is a member of the most massive family of leptons. So, taus may be an important probe for a number of new physics processes.

This paper reports on work in progress on the search for events containing the reaction $W \rightarrow \tau\nu_\tau$ with the subsequent decay of the tau to hadrons. The analysis was performed on events from the 1988-89 run of the CDF detector[5].

Triggering Criteria

Since the tau decays to both electrons and muons, the standard lepton triggers of CDF are sensitive to at least a fraction of tau leptons which are produced through almost any physics mechanism. However, the branching fraction to hadrons for tau decays is approximately 64% as compared to the 18% branching fractions to either an electron or a muon. Therefore, the ability to trigger on the hadronic decay modes of the tau can dramatically increase the number of tau leptons in the data sample. For this reason, CDF experimenters have implemented a tau hardware trigger specifically designed to tag events containing a "tau-like" signature.

Hadronic decays of a tau from a W or Z^0 boson decay appear as jets with modest transverse energy (transverse energy or E_T is defined as the measured energy in the calorimeter multiplied by the sine of the polar angle specifying the position of the energy deposition) in CDF, therefore any trigger designed to tag these decays must contend with the huge backgrounds from QCD dijet and multi-jet processes. Because the tau has a mass which is small compared to the center-of-mass energy, however, there are several characteristics of tau decay jets which are quite different from those of the average QCD jet. The first is that over 98% of the hadronic tau decays produce fewer than four charged tracks. About 78% of these decays have only a single charged track in the final state. In all decays, the number of neutral pions in the final state is three or less. Hence, the charged tracks from tau decays tend to have large transverse momentum (p_T) if the tau itself has large p_T. A second consideration is that the opening angle of the tau jet is relatively small since the mass of the tau is much smaller than its transverse momentum (in the case of taus produced from W or Z^0 decays). A third consideration is that the tau neutrino, which must be present in any decay mode of the tau, can carry off a significant amount of "missing" transverse momentum. Finally, in the case of processes which produce $\tau\bar{\tau}$ pairs, one can demand that one of the taus decays to either an electron or muon, then tag the "tau-like" jet opposite the lepton to identify the event. The efficiency of such an event tag is fairly high since the tau branching ratios to either electrons or muons is approximately 20%.

The CDF tau trigger exploits several of these characteristics. At the second stage of the CDF trigger[6] (Level 2), the tau trigger searches information from the detector in an attempt to find calorimeter clusters which have four or fewer calorimeter towers with E_T greater than 1 GeV, a highest E_T tower or "seed" tower with E_T greater than 3 GeV, a total E_T greater than 10 GeV, and a ratio of E_T in the electromagnetic (EM) calorimeter to total E_T (EM plus hadronic) less than 0.89 (this requirement rejects electron clusters which will be handled by the CDF electron trigger). In addition, the cluster had to be associated with at least one charged track with p_T greater than 4.8 GeV/c as determined by a hardware track processor[7] and not be back-to-back, within 30°, of a typical jet cluster with $E_T > 10$ GeV. Any cluster which satisfied all these requirements was identified as a τ trigger cluster. The Level 2 tau trigger demanded that there be at least one τ trigger cluster plus either another lepton (electron or muon) with E_T greater than 10 GeV as identified by the corresponding lepton trigger, another cluster with EM E_T greater than 20 GeV, or missing transverse energy ($\not{E}_T$) greater than 20 GeV, where $\not{E}_T$ is defined as

$$\not{E}_T = -\sum_{\text{cal. cells}} E_i \vec{u}_T^{\,i}$$

and E_i is the energy deposited in calorimeter cell i. The vector $\vec{u}_T^{\,i}$ is the transverse component of a unit vector from the interaction vertex to the center of calorimeter cell i. Events were also accepted if they had two τ trigger clusters which were within 15° of being back-to-back or if they had at least one τ trigger cluster with E_T greater than 30 GeV. Events with a single τ trigger cluster with 20 GeV $< E_T <$ 30 GeV were prescaled by a factor of 5. The total trigger rate for all tau triggers averaged 0.6 Hz at a luminosity of 10^{30} cm^{-2}/s.

The Level 3 trigger[8] at CDF utilizes the full resolution of the detector and provides a software platform for sharpening trigger cuts. The Level 3 tau trigger utilized the sharper thresholds by reapplying the cuts used in Level 2 to all τ trigger clusters and, in addition, demanded that the "mass" (defined as the sum of the position-weighted E_T of each calorimeter tower in the cluster) be less than 7 GeV. Monte Carlo studies show the mass cut to be 100% efficient for τ trigger clusters generated by real tau decays.

The missing-E_T trigger of CDF also provided a useful sample of tau candidate events. The missing-E_T trigger simply required a $\not{E}_T$ value of 25 GeV or greater as determined by the Level 2 trigger to pass an event. In order to reduce the rate due to spurious noise hits in the hadron calorimeters, an additional requirement was made that the E_T measured in the electromagnetic calorimeters had to be greater than or equal to 8 GeV for the highest E_T cluster in the event. The Level 3 missing-E_T trigger required that the event have $\not{E}_T > 15$ GeV after removal of spurious noise pulses in the calorimeters and demanded that there be no jet back-to-back, within 30°, with the largest E_T cluster in the event.

Search for $W \to \tau\nu_\tau$

A search for the reaction $W \to \tau\nu_\tau$ was performed for data from both the missing-$\mathrm{E_T}$ trigger and the $\tau + \not{E}_\mathrm{T}$ trigger. In the offline processing of the missing-$\mathrm{E_T}$ trigger data (henceforth referred to as the MET stream) only events with $\not{E}_\mathrm{T}$ greater than or equal to 25 GeV and a "significance of missing $\mathrm{E_T}$" greater than or equal to 2.4 were retained in the tau candidate event sample. The significance of missing $\mathrm{E_T}$ ($S_{\mathrm{E_T}}$) is defined as

$$S_{\mathrm{E_T}} = \frac{|\not{E}_\mathrm{T}|}{\sqrt{\mathrm{E}'_\mathrm{T}}} \text{ where } \mathrm{E}'_\mathrm{T} = \sum_i E_i \sin\theta_i. \tag{1}$$

In the offline processing of the $\tau + \not{E}_\mathrm{T}$ trigger data (referred to hereafter as the TAUMET stream), events were required to have $\not{E}_\mathrm{T}$ greater than or equal to 20 GeV and $S_{\mathrm{E_T}}$ greater than or equal to 2.4. In order to ensure that the calorimetry and tracking information was optimal, events in both streams were also required to have a longitudinal (*i.e.* along the beam) vertex position less than 60 cm from the detector center. Finally, to supress the enormous background due to QCD two-jet events in which one of the jets has been significantly mismeasured due to cracks in the detector acceptance, events in either stream were rejected if they contained at least one other calorimeter cluster with $\mathrm{E_T}$ greater than 7 GeV.

Events from both streams were searched for "tau-like" objects. The search began by forming cones of 10° and 30° around the highest $\mathrm{p_T}$ track in the event. All tracks with $\mathrm{p_T}$ greater than 1 GeV/c within the 10° cone were considered to form a track "cluster". Clusters with one or more tracks with $\mathrm{p_T}$ greater than 1 GeV in the region between 10° and 30° were rejected. In order to reject events from the process $W \to e\nu_e$, in which the highest $\mathrm{E_T}$ cluster is an electron, clusters were also rejected if their ratio of hadronic $\mathrm{E_T}$ to EM $\mathrm{E_T}$ was less than or equal to 20%. The trajectories of the remaining clusters were extrapolated to their impact points on the calorimeter. The $\mathrm{E_T}$ for all calorimeter towers within a region 30° in azimuth and 0.6 in pseudo-rapidity (η) surrounding the extrapolated impact point was summed and required to be greater than 15 GeV. Clusters passing all cuts were classed as tau candidates. Figure 1 shows the number of charged tracks in the 10° cone for tau candidates found in the MET and TAUMET streams. The bottom two plots in the figure show the number of tracks in the 10° cone for Monte Carlo events generated with ISAJET[9] for the process $W \to \tau\nu_\tau$. All Monte Carlo events were run through the CDF detector simulation, including a detailed hardware simulation of the Level 2 trigger, then subjected to the same cuts as the MET or TAUMET data streams.

In order to estimate the background to the tau candidate sample, a control sample was generated by selecting events which pass all the cuts of the MET or TAUMET stream except that a second jet, in addition to the tau cluster, of $\mathrm{E_T}$ greater than 7 GeV was *required* to be present. Examination of the events from the ISAJET Monte Carlo sample indicate that fewer

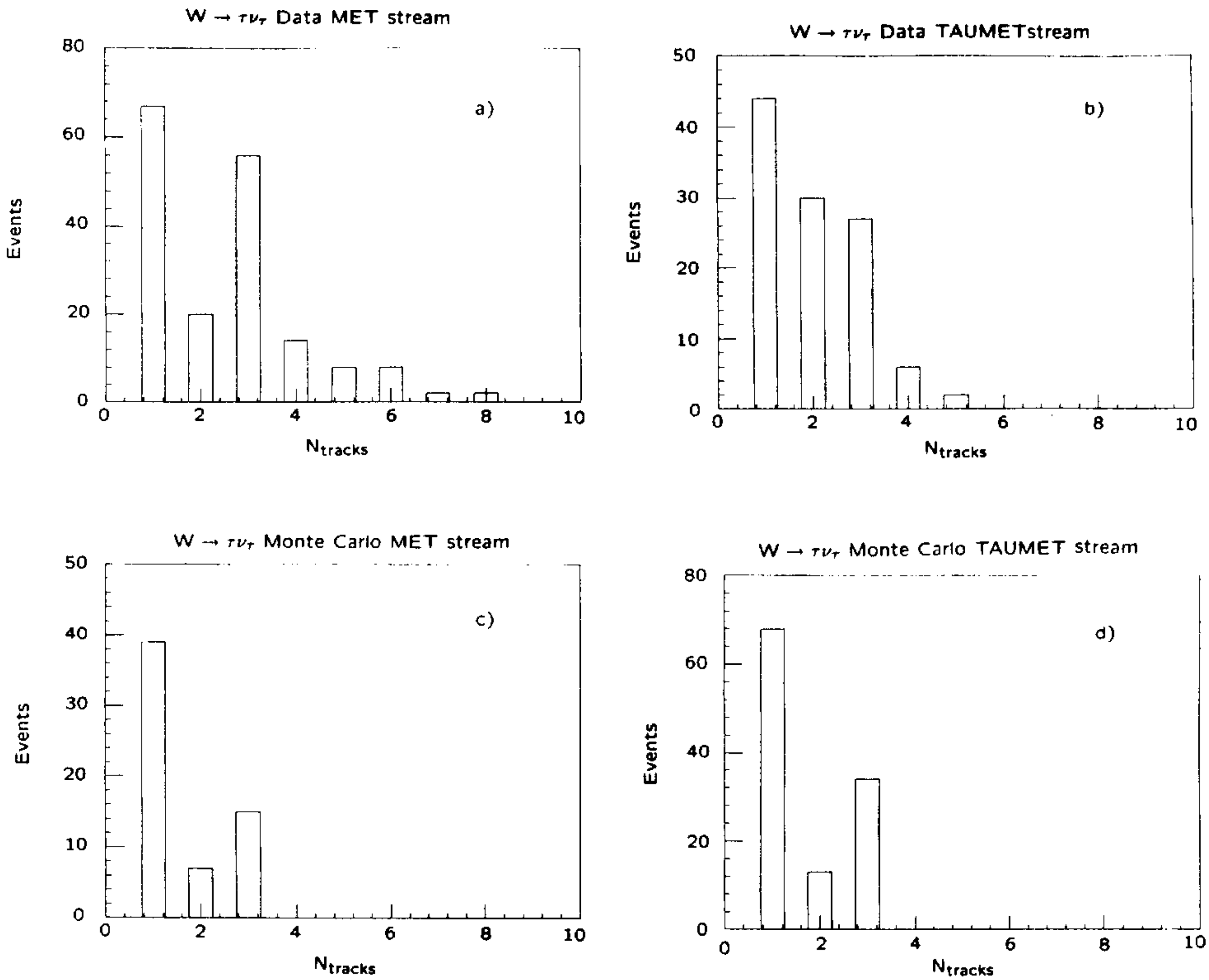

Figure 1: Number of charged tracks in the 10° cone for τ candidates from the
a.) MET stream for real data
b.) TAUMET stream for real data
c.) MET stream for Monte Carlo data
d.) TAUMET stream for Monte Carlo data as explained in the text.

than 10% of real $W \rightarrow \tau\nu_\tau$ events will have a second jet passing this requirement. A second control sample was generated using events containing a tau cluster and a high p_T electron. Studies of events with electron E_T between 12 and 20 GeV indicate that many of these events result from QCD production of bottom quarks at the Tevatron[10]. Again, events were required to pass all of the cuts for the MET or TAUMET streams except that a high p_T electron was demanded. Figure 2 shows plots of the number of charged tracks inside the 10° cone of the tau cluster for dijet and electron plus jet events passing the MET or TAUMET stream cuts. There is a clear excess of events in the region of three or more tracks for both the control samples even though the kinematic cuts used to define the tau clusters are essentially identical to those of the tau data sample.

Assuming that the control samples are representative of the backgrounds which actually mimic taus for CDF, the shapes of the dijet and electron plus jet plots for the number of tracks in the 10° cone can be used to derive a background-subtracted plot for the number of tracks distributions for the tau data sample. Here, the total number of events with $N_{\text{tracks}} > 3$ in the dijet (electron plus jet) sample have been normalized to the number of events with $N_{\text{tracks}} > 3$ in the MET or TAUMET data samples. The shape of the dijet (electron plus jet) sample was then used to estimate the number of background events in the $N_{\text{tracks}} = 1, 2,$ and 3 bins of the data samples. Figure 3 shows the results of subtracting the estimated background due to each of the control samples from either of the data samples. These plots are very preliminary.

Since this analysis has focussed on locating only the hadronic decay modes of the tau, it is possible that one of the "intermediate" decay products of the tau, such as the ρ meson can be reconstructed from the data sample, providing the data sample is not dominated by background. Since the $\rho^\pm$ decays to $\pi^\pm\pi^0$, only the events in the tau data sample which have a single charged track in the 10° cone have been considered for such a search. In order to reconstruct a mass, it is best to use the momentum of the charged track (which is measured with a resolution of $\Delta p_T/p_T^2 \sim 0.17\%$) while the energy of any neutral cluster found in the calorimeter near the impact point of the charged track is best measured by the strip chambers which lie approximately 6 radiation lengths deep in the central EM calorimeters. Figure 4 shows the invariant mass for the single charged track plus a single nearby neutral cluster, as measured by the strip chambers for the tau data sample and the dijet control sample. There is a clear enhancement near the ρ mass of 0.77 GeV/c^2 for the tau data sample.

Conclusion

While there are still many studies which must be done in order to verify the existence of taus in the CDF data sample, it is possible to make a preliminary conclusion that the sample of events with a single, narrow, isolated jet does appear to be significantly different from the background expected from QCD production of either light or heavy quarks. In addition, there

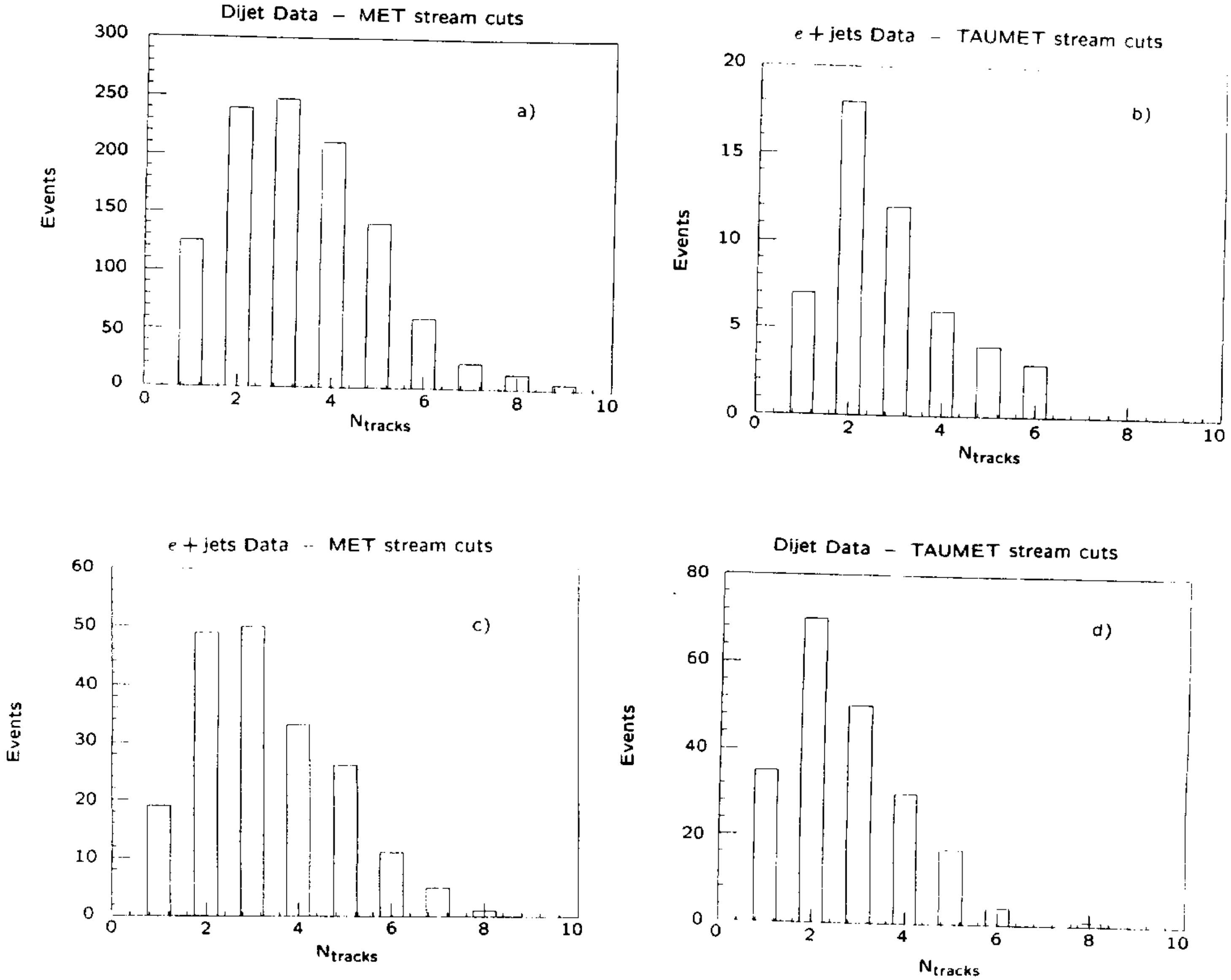

Figure 2: Number of charged tracks in the 10° cone for τ candidates from the
a.) MET stream cuts on dijet data
b.) TAUMET stream cuts on electron plus jet data
c.) MET stream cuts on electron plus jet data
d.) TAUMET stream cuts on dijet data.

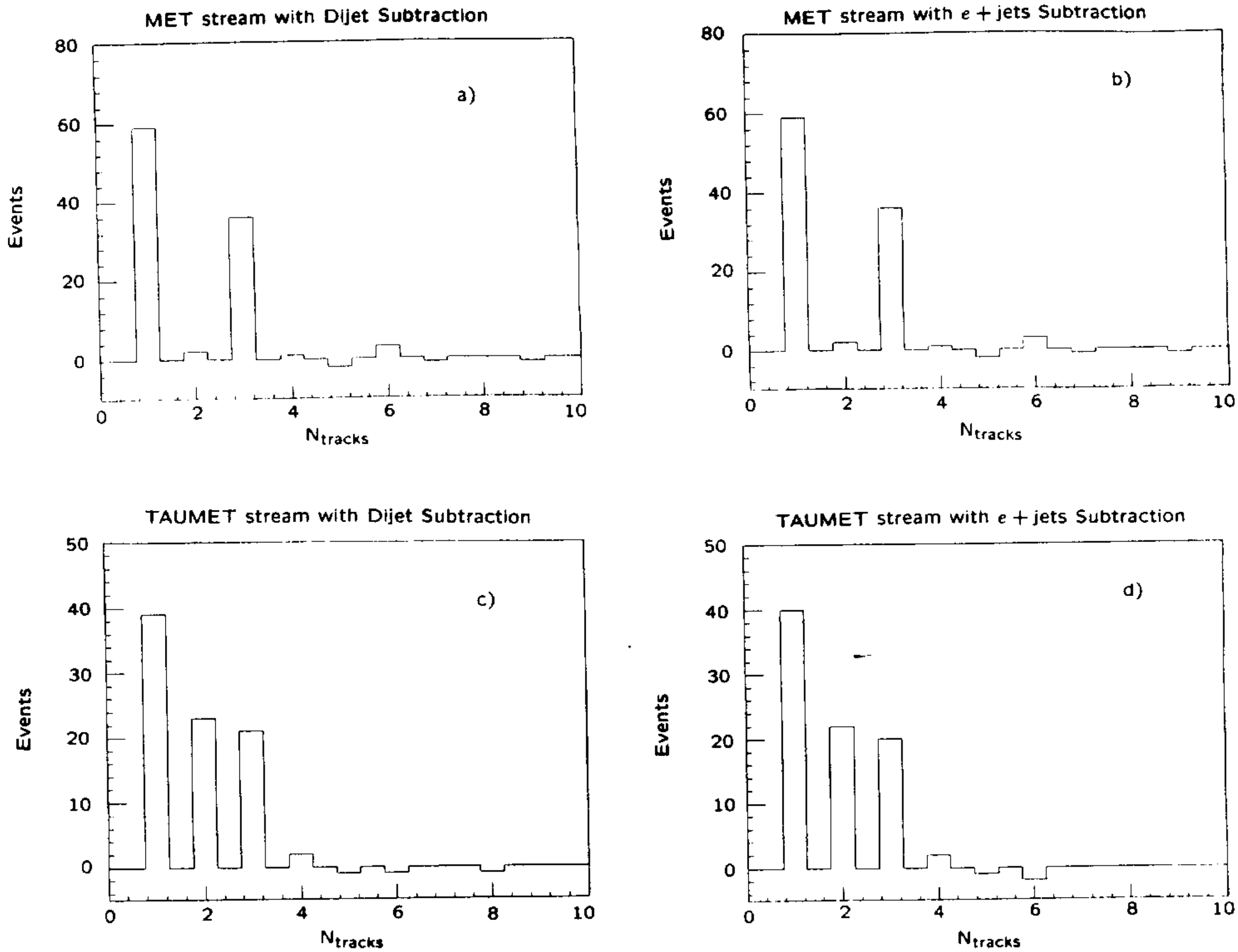

Figure 3: Background-subtracted plots for the number of charged tracks in the 10° cone for τ candidates from the
a.) MET stream with background estimated from the dijet control sample
b.) MET stream with background estimated from the e plus jet control sample
c.) TAUMET stream with background estimated from the dijet control sample
d.) TAUMET stream with background estimated from the e plus jet control sample.

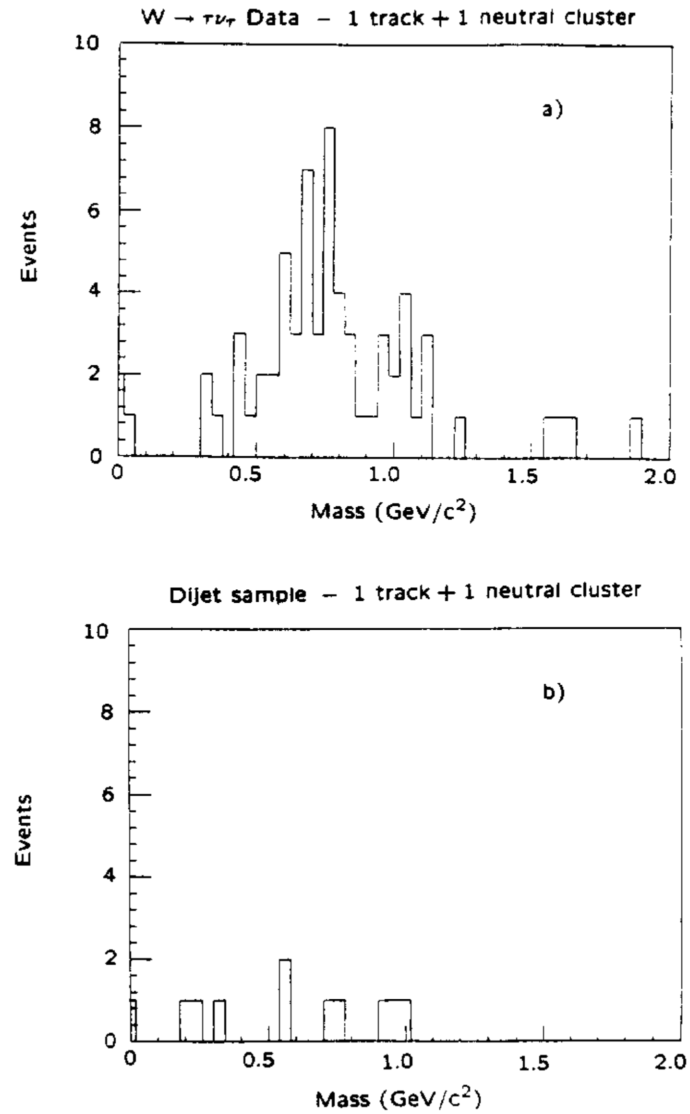

Figure 4: Invariant mass of single charged track plus single strip cluster events for
a.) the tau data sample
b.) the dijet data sample.

are some indications that a charged rho mass peak can be reconstructed from the single charged track events in the tau data sample. No such peak appears in the dijet control sample. By estimating the efficiencies for all trigger and offline cuts made on the tau data sample, it is preliminarily concluded that the number of tau candidate events observed is not inconsistent with the expectation due to universality of the weak charged current couplings.

References

[1] CDF is a collaboration of the following 18 institutions: Argonne National Laboratory, Brandeis University, University of Chicago, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Harvard University, University of Illinois, National Laboratory for High Energy Physics (KEK), Lawrence Berkeley Laboratory, University of Pennsylvania, Istituto Nazionale di Fisica Nucleare (Pisa), Purdue University, Rockefeller University, Rutgers University, Texas A&M University, University of Tsukuba, Tufts University, and University of Wisconsin.

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